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ABSTRACT

This paper describes the various laboratory and field tests conducted to assure that flow-induced vibrations do not exist in the piping thermowells of the Fast Flux Test Facility. FFTF thermowells are subjected to a wide range of flowing sodium velocities during testing and operation. Early design work indicated a need to provide special attention to thermowell response in the drag direction at the higher sodium flow rates associated with FFTF testing. The results of this study provide some additional insight into response characteristics of a tube in liquid cross flow with emphasis on motion in the drag direction.

INTRODUCTION

The Fast Flux Test Facility (FFTF) thermowells are used to monitor liquid sodium temperatures during transient and steady-state conditions and are a vital element in the Plant Protection and Control Instrumentation. Typical FFTF thermowell configurations are shown in Figure 1. The thermowell probes are installed in 3, 8, 16 and 24 inch diameter piping. These probes penetrate the moving sodium stream and are subject to vortex shedding forces in the lift and drag direction.

During design qualification of the FFTF thermowells, the early work identified a need to provide additional verification of the response of the Type A thermowells in the drag direction at the higher sodium flow rates associated with FFTF testing. For cylinders in gas flow, the oscillatory drag force is generally insufficient to cause significant stress. However, the greater density of liquid sodium increases the drag forces sufficiently to be a potential problem at resonance.

This paper describes the various laboratory and field tests conducted to evaluate and guard against damaging flow induced vibration of the piping thermowells in the FFTF. Well known resonant conditions associated with lift forces due to vortex shedding were evaluated and kept out of the operating range. However, of special interest was the drag direction thermowell responses at high flow rates in large diameter (>8") piping. These were excitable when the vortex shedding frequency corresponded to half the fundamental frequency of the thermowell. The work reported herein was a major ingredient leading to structural qualification of the FFTF thermowells.

LABORATORY WATER FLOW TESTS

The first series of water flow tests was done using a test section consisting of a 20 foot segment of 4 inch diameter schedule 40 stainless steel pipe. This test section had both a Type A and Type B thermowell welded into the branch of a 4:1-1/2 inch tee. Each thermowell system was instrumented with drag and lift direction accelerometers at three locations: 1) inside

the thermowell stem, 2) on the simulated connection head mass, and 3) on the thermowell base (welded to the branch of the reducing tee) to measure structurally borne loop piping vibrations.

In an effort to remove possible outside sources of vibratory motion to the thermowells, both ends of the test section were isolated from the rest of the loop by rubber sections 3 feet long. In addition, the test section was supported at five locations by rigid supports which were bolted into a concrete floor. Figure 2 shows the thermowell installed in the 4:1-1/2 inch tee, instrumented with accelerometers and mounted on a shake table to determine the natural frequency of the thermowell prior to installation in the test section.

Flow velocities up to 65 ft/sec, over twice the maximum flow rate in FFTF sodium piping, were achieved. The objectives of these tests were to determine the vibration response of the instrumented thermowell systems as a function of water flow velocity and to search for possible vibration responses that could compromise the structural integrity of the thermowell or piping.

During the flow testing it was found that the vibration amplitudes of the exposed thermowell stems were strongly influenced by the absence or presence of coupling with the connecting pipe structure. The structural changes required to affect or eliminate coupling were subtle. Considered as isolated components in the absence of such coupling, the thermowells responded to the water flow excitation with narrow-band random vibrations centered about the fundamental natural frequency of the stem in water. The vibration amplitudes were generally small. Under these conditions no flow-dependent resonant conditions or instabilities were observed over the flow rates tested.

When vibration coupling provided interaction with the connecting pipe and/or support structure, the thermowell stem response was significantly changed and generated relatively large, almost sinusoidal vibration amplitudes in the drag (parallel-to-flow) direction. In the case of the Type A thermowell, the coupling involved a shell type ovalling mode of the water carrying pipe. When the flow velocity dependent resonance was established, the pipe walls

vibrated at the natural frequency of the thermowell stem. Figure 3 shows typical response of the Type A thermowell stem during resonant and nonresonant conditions. Application of a simple circumferential clamp around the test section near the thermowell would inhibit the Type A thermowell resonance.

The Type B thermowell responses increased monotonically with flow velocity up to about 45 ft/sec with some indication of resonant gain above this flow rate. The vibration response was most substantially influenced by structural coupling, if present, at flow velocities about 45 ft/sec. Figure 4 shows the typcial response of the Type B thermowells.

Comparison of post- and pre-test examinations provided no indication of damage to the tested thermowells as a consequence of vibration excitation. The simulated connection head masses mounted to the thermowell extension tubes were not excited to significant vibration levels during the testing.

As a result of these initial thermowell vibration tests, (see Table 1) the possibility of thermowell system resonance occurring in a typical FFTF installation could not be ruled out. Even though the resonant buildup in the tests occurred above the maximum design flow rate for any piping that contained thermowells, the test section was non-protypic in the following respects:

Pipe Size:	Initial tests used 4 inch schedule 40 SS pipe. FFTF thermowells are installed in 8, 16 and 24 inch schedule 40 SS pipe in the main Heat Transport System and in 3 inch schedule 40 SS pipe in the Closed Loop Systems.
Orientation:	Initial tests had the thermowells oriented vertical to the pipe center. FFTF installation has them installed at $10^{\circ}{}^{+5^{\circ}}_{-2^{\circ}}$ above the horizontal (see Figure 5).
Imersion Depth:	Initial test thermowell stems penetrated 1.78 inches into the cross section of the 4 inch diameter pipe. FFTF thermowells have a nominal imersion depth of 1.68 inches in all pipe sizes.

Pipe Attachment: Initial test thermowells were installed using a standard piping tee. FFTF installations use a sweepolet design to attach the thermowells to the piping (see Figure 5).

Since the thermowell vibration response in these initial tests seemed to indicate a strong dependence on coupling with the connecting piping it was difficult to make specific conclusions regarding the adequacy of the FFTF installations. The difference mentioned above could all directly or indirectly affect the coupled response. It was therefore decided to do additional thermowell/pipe vibration testing.

The follow-on tests were conducted using prototypic 8, 16 and 28 inch diameter pipe spool pieces with Type A thermowell installations. A water flow test loop was designed with 8 inch diameter pipe and Type A thermowell and flow tested up to velocities of 45 ft/sec. Because of loop restrictions, this was the largest pipe size that could be flow tested. The test objectives were to: 1) investigate the modal response characteristics of the thermowell/pipe assemblies, 2) measure the thermowell stem accelerations and strains during waterflow and combined flow/shaker testing on the 8 inch diameter pipe section.

Typical strain gage and accelerometer instrumentation for the follow-on waterflow tests on 8 inch diameter pipes are shown in Figure 6. Test data were acquired during shaker excitation from two rows of four equally spaced accelerometers installed circumferentially on the pipe sections, located six inches upstream and downstream from the thermowell centerline. In addition, a hand-held accelerometer was used to locate node lines on the piping.

TEST PROCEDURE

Modal Investigation

Testing was conducted with each of the 16- and 28-inch-diameter pipe sections cradled in two nylon straps and suspended from an overhead crane. A small (5.5 pound) shaker was attached to the pipe section 20 inches from the thermowell centerline. Constant force sinusoidal swept-frequency excitation from 100 to 1500 Hz was applied at two circumferential locations, parallel

and orthogonal to the thermowell longitudinal centerline. Pipe and thermowell stem response data from nine accelerometers, in addition to the shaker force data, were reduced to co-quad plots, and the significant response peaks were chosen for mode shape investigation. Shaker excitation was then applied at each of the significant response peaks and, with the use of a hand-held accelerometer, node lines were located and mode shapes defined.

The modal investigation of the 8-inch-diameter pipe section followed the same procedure as described above, with the following exceptions:

1. The pipe section was installed in the flow loop.
2. Investigations were performed (a) with no water in the flow loop and (b) with the loop filled with water (zero flow velocity).

Flow Testing

Flow testing, using water at 100°F, was performed in four phases, as described below:

1. A flow sweep was performed as tabulated:

Flow Rate		Δ Flow Rate	
ft/sec	GPM	ft/sec	GPM
10 - 28	1560 - 4360	2	312
28 - 36	4360 - 5620	1	156
36 - 40	5620 - 6240	2	312

   PSD plots of thermowell stem acceleration and strain were made and all transducer outputs (20) were recorded on magnetic tape.

2. A flow sweep was performed in 0.25 ft/sec flow increments from 20 to 37 ft/sec, observing thermowell stem acceleration in the drag direction, to ascertain that a response peak had not been missed. Testing done in 1, above, was extended to 45 ft/sec.
3. A flow sweep was performed at 0.25 ft/sec flow increments from 10 to 36 ft/sec while exciting the test section with the shaker at the thermowell stem fundamental response frequency.

4. A flow sweep was performed in 1.0 ft/sec flow increments from 20 to 36 ft/sec while introducing swept-frequency excitation from 300-1300 Hz to the test section from the shaker at each flow increment.

TEST RESULTS

Modal Investigation

Typical results of the modal investigations are shown in Figure 7. On each pipe section, there were higher pipe modes which closely bracketed the thermowell stem fundamental frequency as shown below:

Thermowell and Adjacent Pipe Response Frequencies

Pipe Diameter Inches	Thermowell Response Frequency, Hz	Adjacent Pipe Response Frequencies, Hz
8 (dry)	1278 (lift axis) 1258 (drag axis)	1265, 1325
8 (wet)	1186 (lift axis) 1187 (drag axis)	1160, 1173, 1202
16	1095 (lift axis) 1093 (drag axis)	1063, 1105
28	1118 (lift axis) 1086, 1106 (drag axis)	1053, 1074, 1088 1123

Flow Testing

Plots of thermowell stem tip RMS displacement and stem root RMS strain vs. mean flow rate are shown in Figures 8 and 9; these data were compiled from PSD plots during the initial flow sweeps. PSD plots exhibited a single dominant peak at the thermowell stem fundamental response frequency, the amplitude increasing in a nominally monotonic manner with increasing flow. PSD plots were generated for selected pipe-mounted accelerometers, and although acceleration levels were very low the following observations were made: 1) dynamic flow-generated forces excited nearly all of the identified pipe modes, and 2) the largest response peak was caused by the thermowell stem motion coupling with pipe.

Response amplitudes observed during the initial flow sweeps were quite low and no resonant buildup was noted. Additional testing was performed as described in Items 2 through 4 above, while monitoring the drag axis accelerometer output on an oscilloscope to check for narrow band resonance. At no time during this testing were other than relatively low monotonically increasing accelerations observed as the flow rate was increased.

To explore the possibility that vortex shedding excitation could be identified, the flow rate was increased from the originally specified 40 ft/sec to 45.5 ft/sec (facility limitation - pump pressure). If vortex shedding provided significant drag direction excitation a response peak should have been evident as the vortex shedding frequency passed through the thermowell stem (one-half natural) frequency. (The flow velocity at which the vortex shedding frequency was one-half the thermowell stem natural frequency was calculated to be 40 ft/sec.) As shown in Figures 8 and 9, vortex shedding excitation is not discernable.

The question of why the first test series produced significantly higher Type A thermowell tip displacements at 32 ft/sec remains unanswered. A possible explanation could be that the earlier tests were somewhat non-prototypic as discussed earlier. The most significant aspect being the propensity of the thermowell/pipe coupling. The fundamental ovulating frequency for the 4 inch pipe was determined by the first test series to be about 1300 Hz, which is relatively close to the Type A thermowell fundamental frequency of about 1150 to 1250 Hz. The larger pipe sizes (8", 16" and 24") used in the second tests and prototypic of FFTF piping have fundamental ovulating frequencies much lower than the thermowell fundamental.

Although there are some differences in the first and second series test results, both tests provided data that indicate the thermowell flow-induced vibration would not be damaging over the design flow rates of the FFTF sodium piping. This conclusion was supported by analytical studies, in addition to the testing described above.

FFTF PLANT TESTING

During a FFTF pre-operational test design to investigate a flow instability phenomena in the plant, a "singing" sound was heard emanating from one group of three thermowells in the secondary piping. During this testing, the piping loops were valved such that this particular section of piping was experiencing flow rates approximately 30% above design flow rates.

Since this was a condition that had not been previously experienced during plant testing it was felt necessary to quantify the extent and severity of the vibration regarding thermowell structural integrity for the plant testing and operating conditions.

A series of field tests at 400°F and 600°F were designed and conducted to determined the magnitude of the thermowell vibration, the extent of the problem on the approximately 70 plant thermowells. Potential field fixes were to be tested if the condition was determined to be detrimental to thermowell structural integrity.

Survey tests were run on all primary and secondary loop thermowells. Accelerometers were attached to thermowell stems and data was collected for various flow rates up to 20% above design flow. Relationships were established to correlate the control accelerometer to thermowell tip displacements and stress levels using the previous water test accelerometer data and design analyses. All of the plant thermowells were either instrumented or monitored audibly during this testing.

TEST RESULTS AND OBSERVATION

A series of flow tests were conducted to verify that the "singing" group of three thermowells were vibrating at their natural frequency. These tests confirmed the presence of a characteristic 1170 Hz frequency at amplitudes high enough to warrant further investigation at flow rates associated with plant Maximum Isothermal System Testing (MIST). Vibration/

flow surveys were the run on all primary and secondary loops to detect other active thermowells. Samples in each group of three thermowells (in general 2 out of a group of 3) were instrumented and audible monitoring was done on all thermowells. All of the Type A thermowells were instrumented in the primary system. The only thermowell found to show other than low level monotonic vibration was in the group that was initially heard "singing".

During the plant testing, flow vibrations in the secondary loops and possibly other factors which we have been unable to quantify have affected the reproducibility of resonant vibration data. As time passed during the testing there was a significant decrease in the noise and in vibration amplitude of the "singing" thermowell.

Pipe clamp adjustments upstream and downstream of the noisy thermowell group were effective in changing the thermowell vibration amplitude. The effect was readily observable by listening to the sound and by observing the accelerometer amplitudes on an oscilloscope. The amplitude could be changed by rotating the clamp on the pipe and/or tightening the clamp. Clamps approximately 6 inches upstream and 6 inches downstream of the thermowell group were added and adjusted during this series of tests.

Other external means were tried to influence the vibration amplitudes. A split collar was designed to be clamped on the outside of the thermowell stem. Damping devises were inserted into the thermowell. These devises had no apparent influence on thermowell vibration amplitude. In addition, a devise designed and calibrated to measure tip deflection was inserted into several thermowells. This devise did tend to reduce vibration amplitdue though its effect was difficult to quantify because the thermowell tip motion was below the sensitivity threshold of 1/4 Mil for the instrument.

Table 2 is a chronological summary of the FFTF thermowell test series It was concluded from this testing,and analysis of data,that the higher than normal amplitude of vibration observed on one group of three Type A thermowells was well within the limits of structural acceptability for the design life of the plant as well as the Maximum Isothermal System Testing which induces flow rates above design for short periods. There was no indication that other

thermowells were experiencing other than normal monotonically increasing vibration amplitudes with flows up to 120% above design flows, which covers all normal operation and test conditions for FFTF.

CONCLUSIONS

Designers of thermowell installations should strive to avoid coincidence or proximity of the piping, pipe support, and thermowell natural frequencies. If such a design is not feasible or practical, it may be possible to provide simple clamping arrangements that are capable of detuning the piping system in the field.

Drag direction as well as lift direction resonant conditions needs to be considered in thermowell design. The coincidence of a vortex shedding frequency with one-half of the thermowell natural frequency should be avoided as well as the one-to-one coincidence that is well recognized as a potential source of lift direction vibration excitation.

Extensive testing and analysis have verified the FFTF thermowell design structural adequacy for normal flow rates and higher flow rates associated with MIST testing.

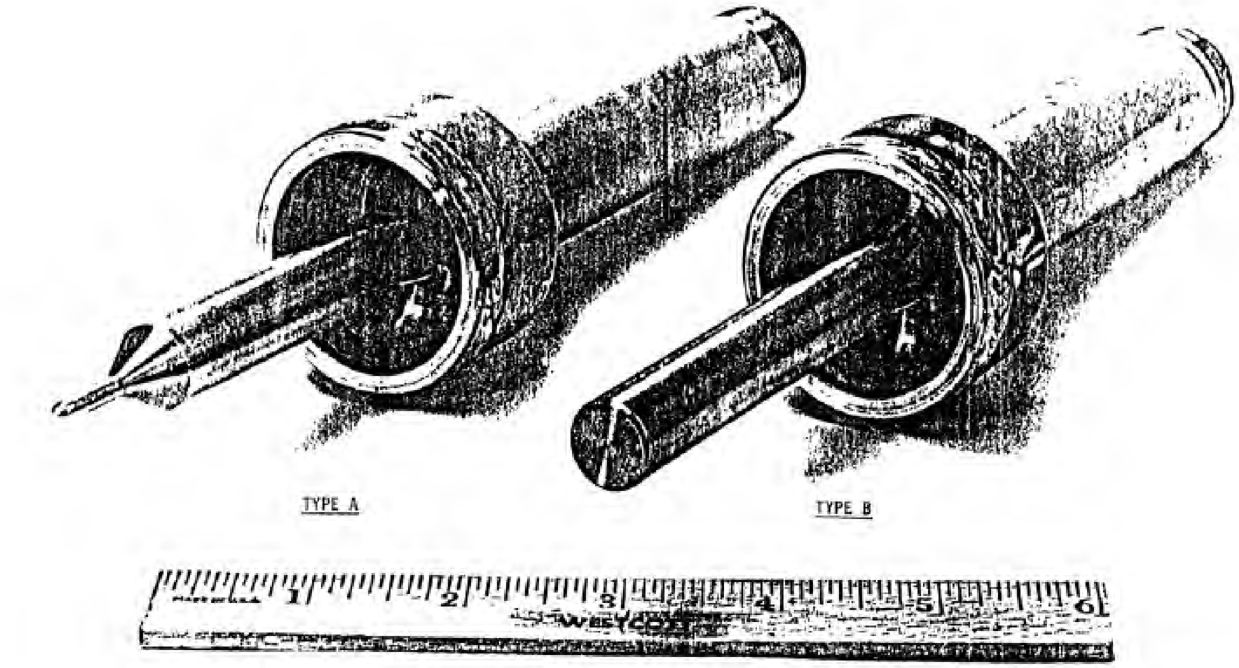


FIGURE 1: TYPICAL FFTF THERMOWELLS

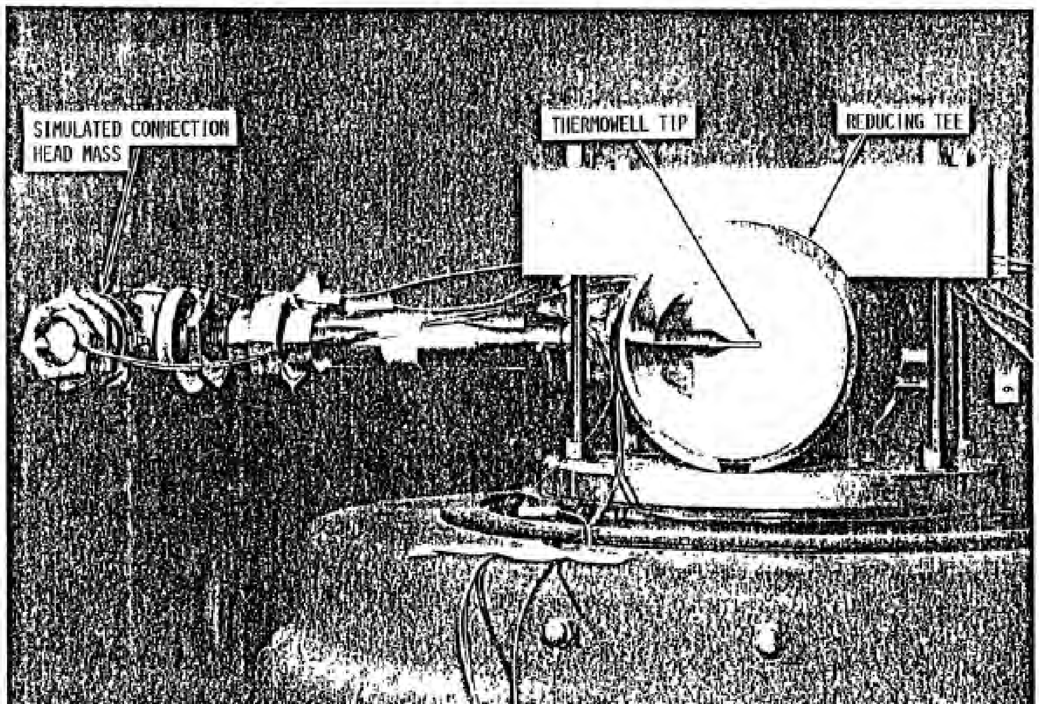


Fig. 2. Type A thermowell mounted on vibration exciter for natural frequency determination

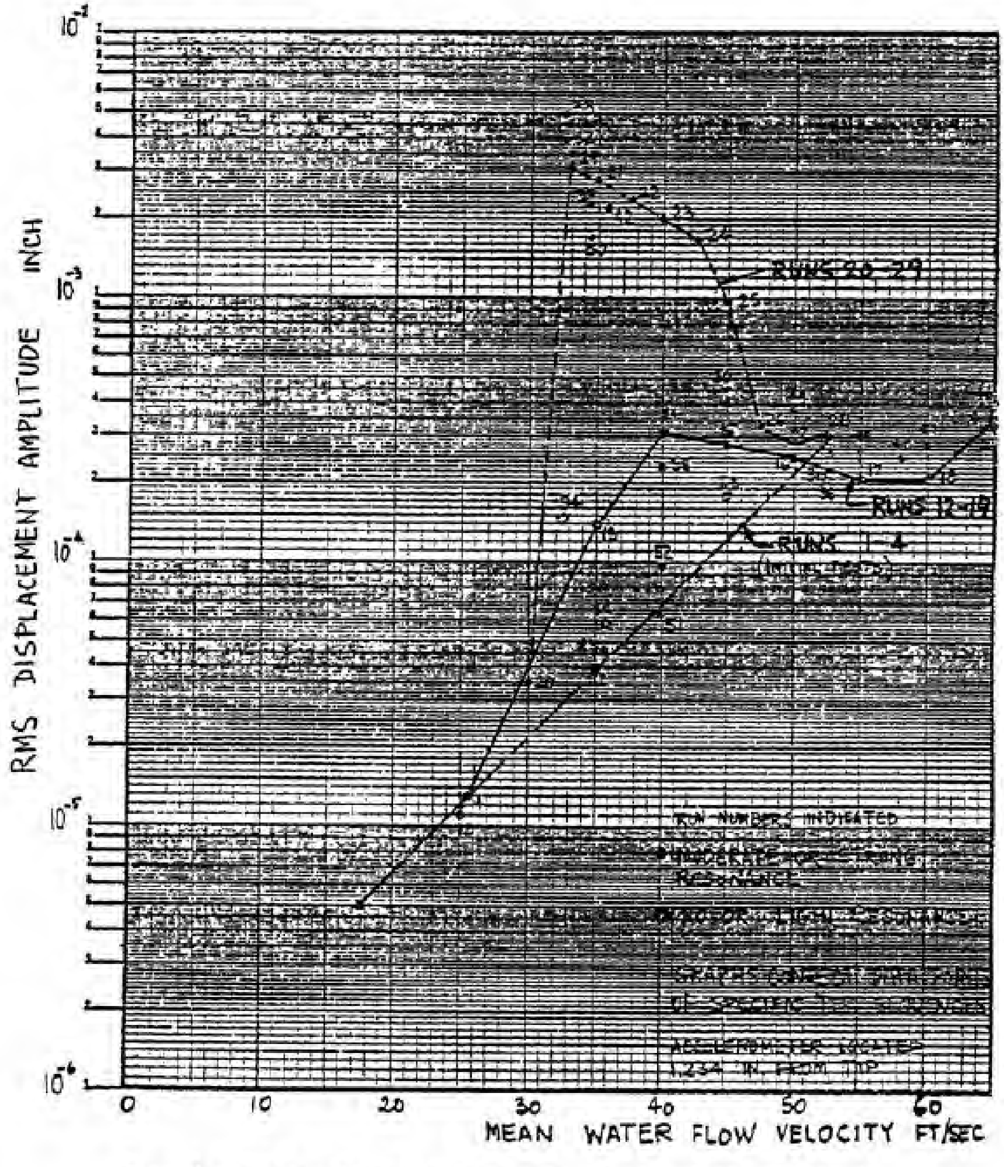


Fig. 3. RMS displacement amplitude of Type A thermowell in drag direction vs. mean water flow velocity

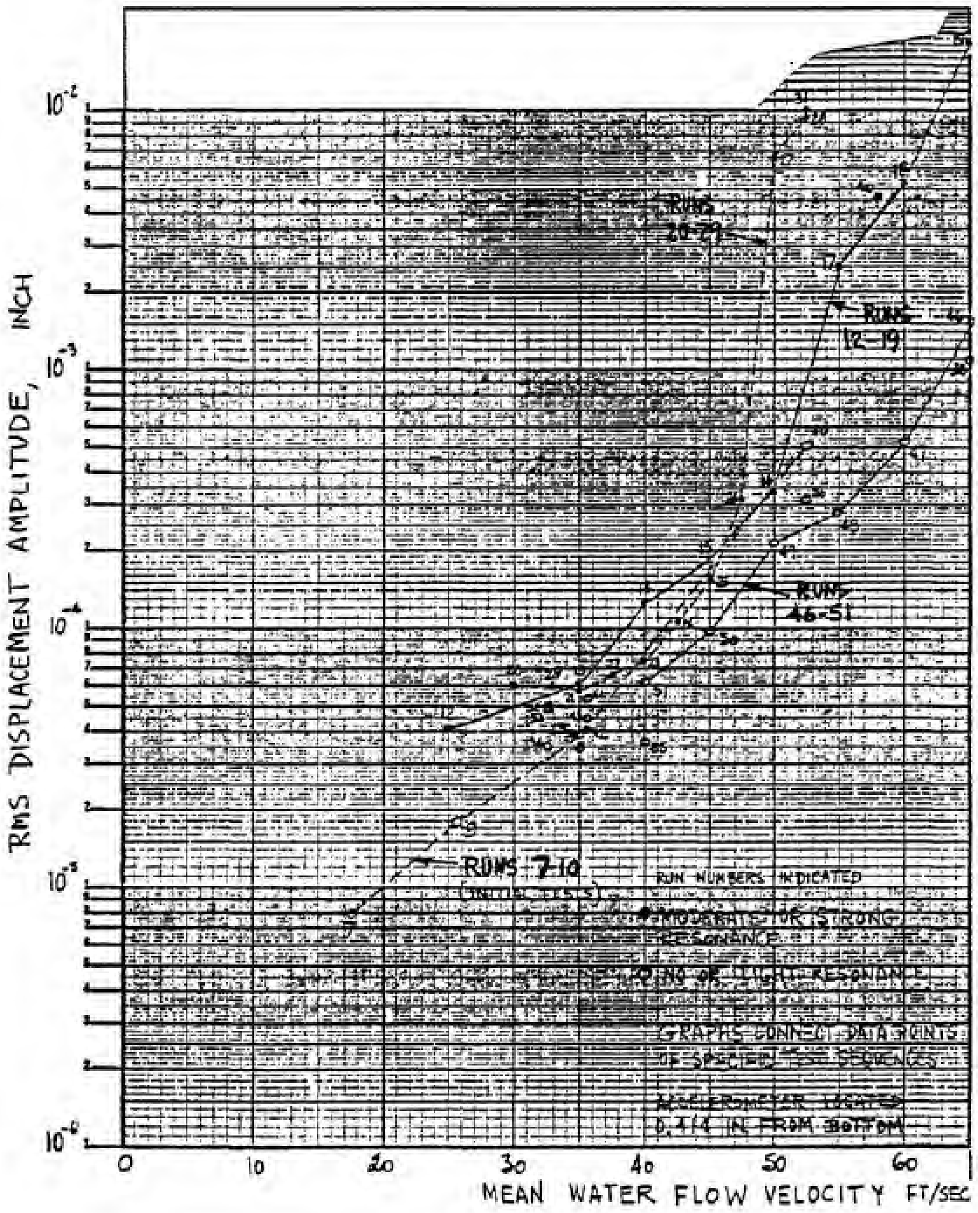


Fig. 4. RMS displacement amplitude of Type B thermowell in drag direction vs. mean water flow velocity

FIGURE 5: TYPICAL THERMOWELL INSTALLATION IN PIPING

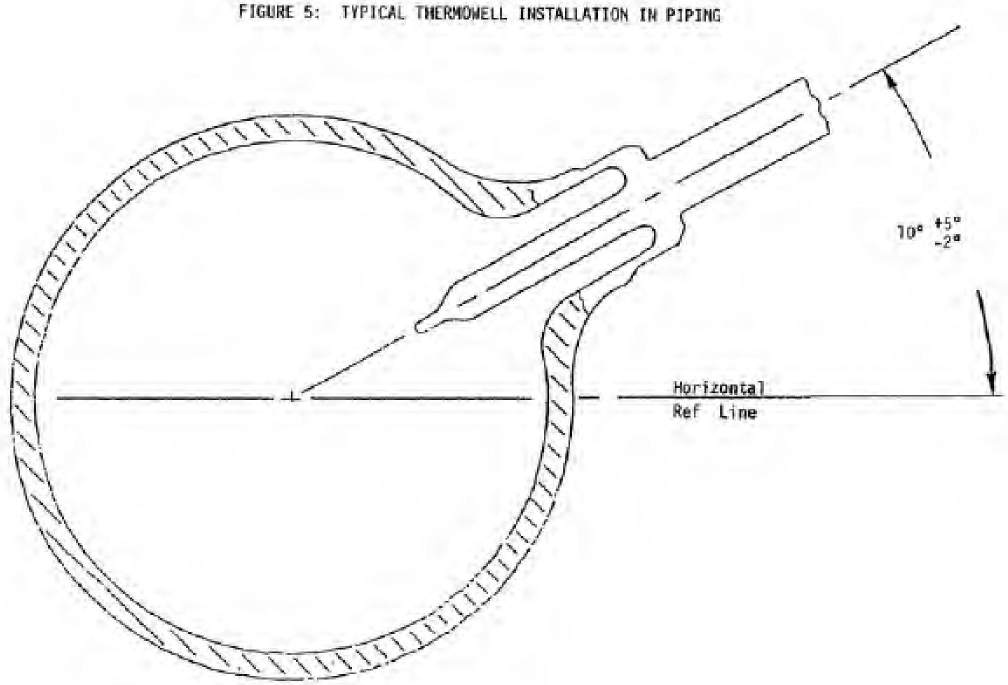
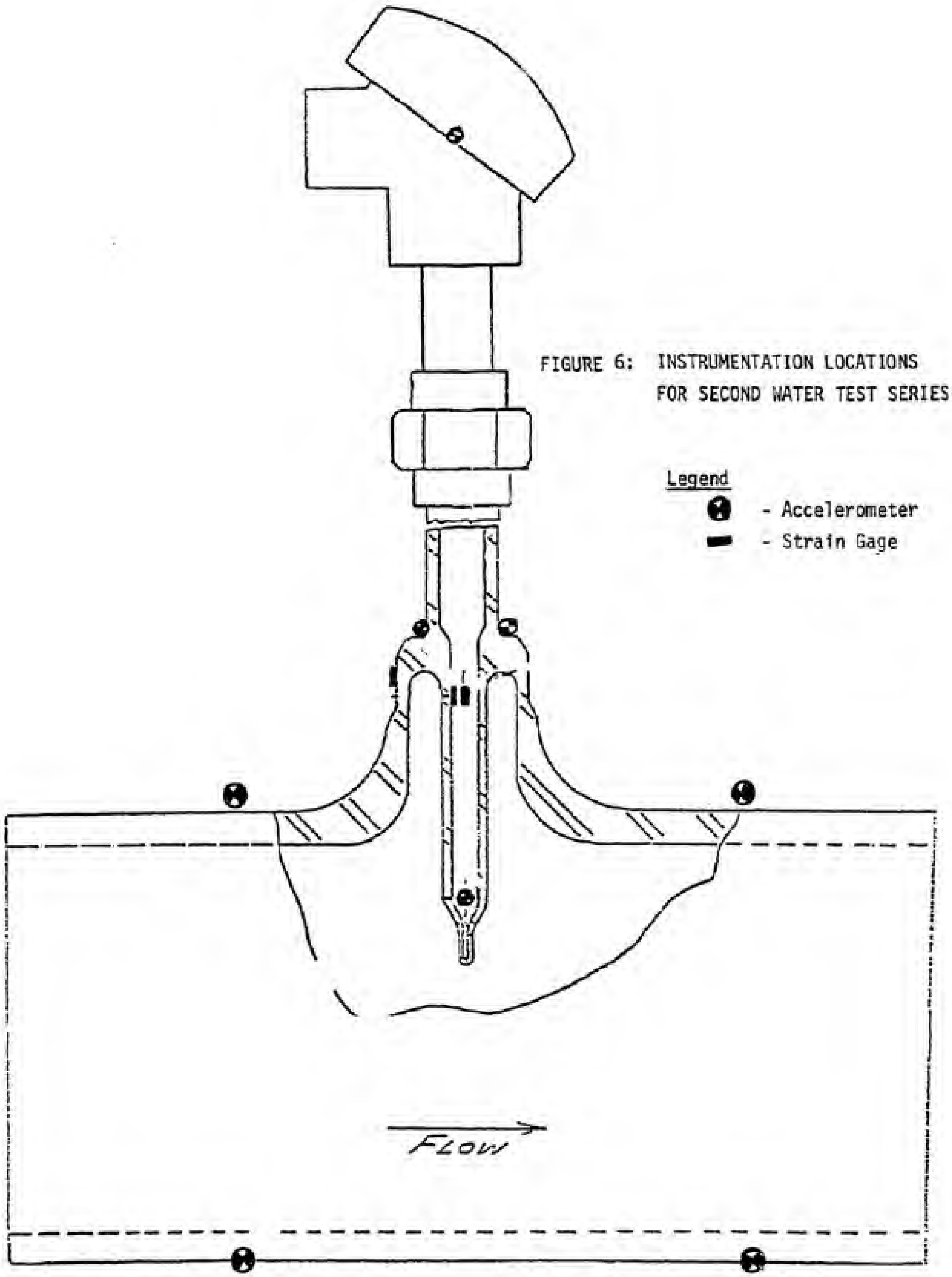


FIGURE 6: INSTRUMENTATION LOCATIONS FOR SECOND WATER TEST SERIES



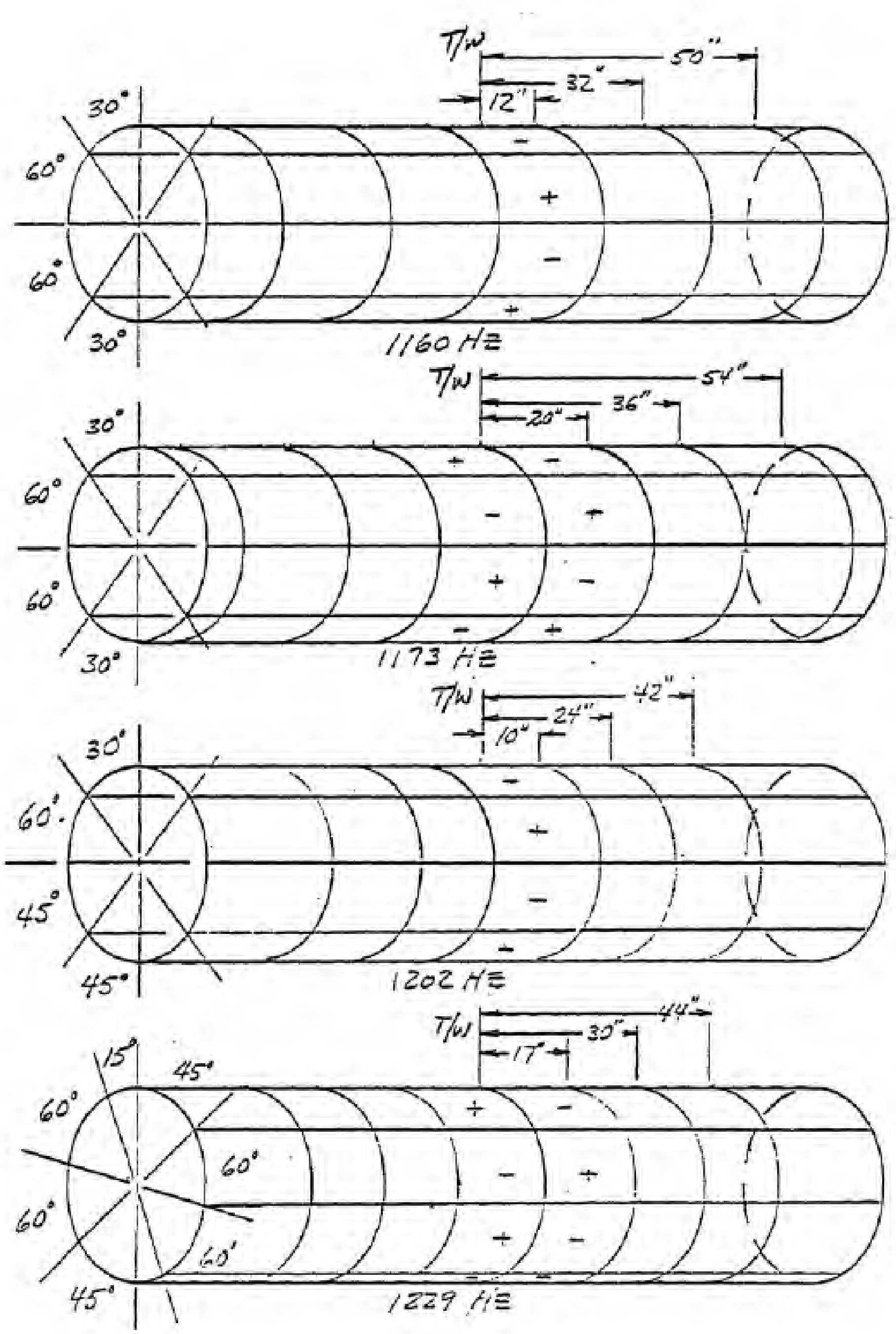


FIGURE 7: TYPICAL 8 INCH DIAMETER PIPE MODES

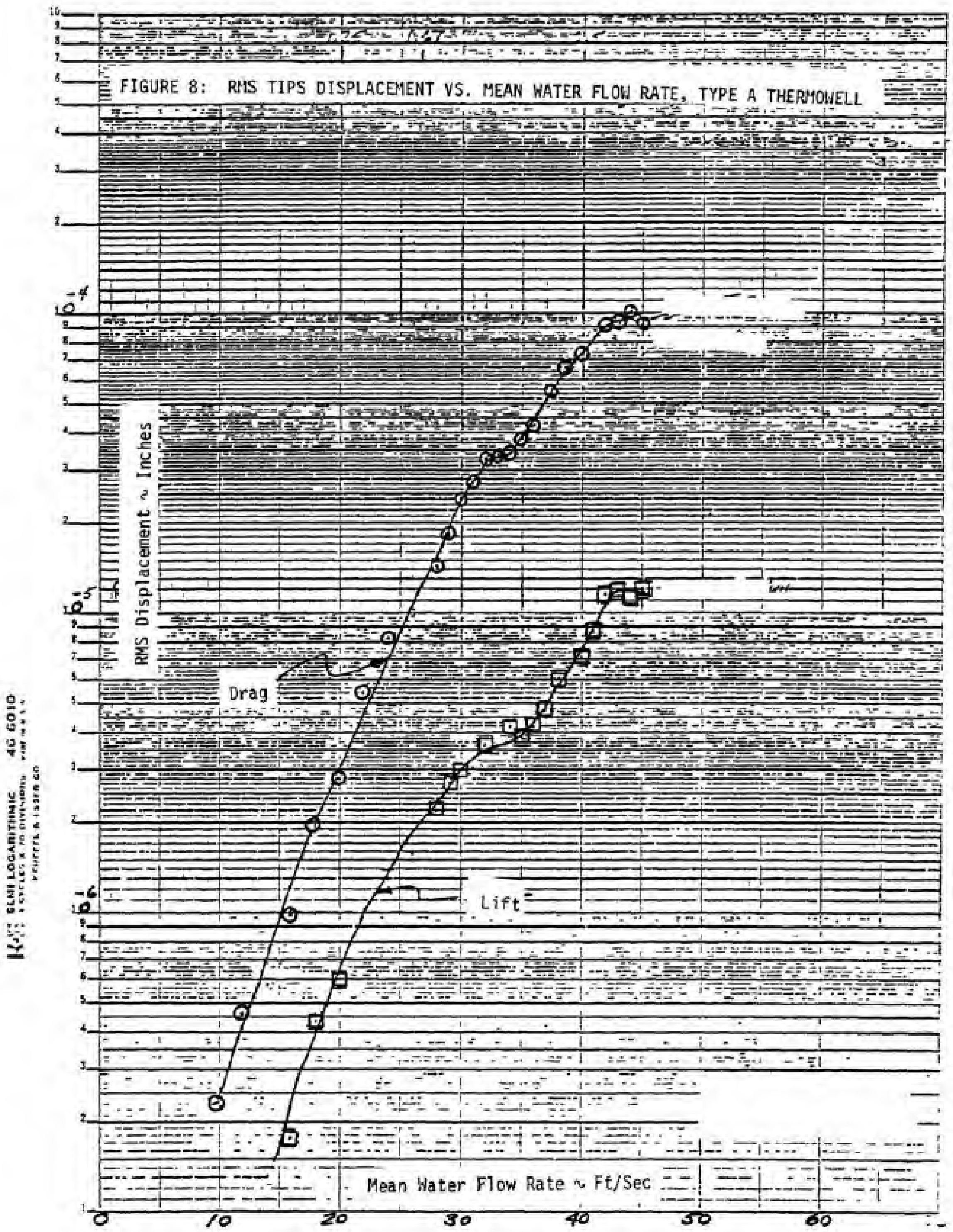


FIGURE 8: RMS TIPS DISPLACEMENT VS. MEAN WATER FLOW RATE, TYPE A THERMOWELL

FIGURE 9: THERMOWELL STEM ROOT STRAIN VS. FLOW RATE

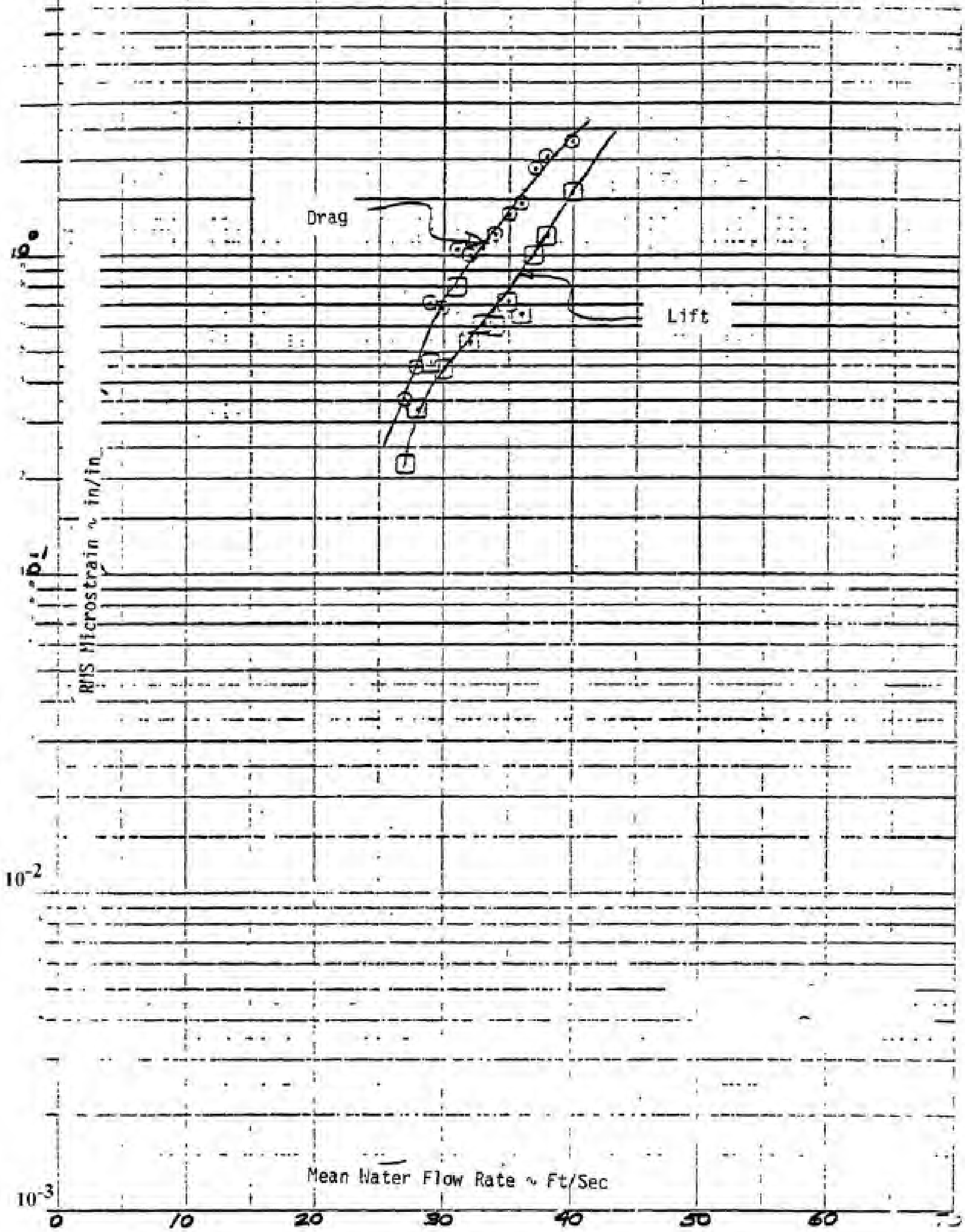


TABLE 1: TEST SECTION SUPPORT AND/OR CLAMPING CONDITIONS

Test Run Number	Description	Resonance Effect* On Stem Drag Direction Vibration Amplitudes — Thermowell Type A	B
1-10	Initial Tests. Test section moderately clamped at all five support locations.	None	None
11-19	Additional testing begun after 4-1/2 month intermission. No intentional changes made.	Light	Moderate
20-32	Continued one week later. No intentional changes made.	Strong	Strong
33	Test section support clamps firmly tightened.	Strong	No Data
34-38	Clamps at the two supports up- and downstream of thermowell A were kept loose. Other three supports clamped tight.	None	None, **
39-42	Test section resting on support with all clamps loose.	Strong	Strong, **
43	Same as Runs 39-42, except that circumferential clamp applied to pipe run (i.e., not at or next to the supports) to eliminate thermowell A resonance.	None	No Data
44	Test section support clamps firmly tightened, circumferential pipe clamp applied.	None	No Data
45-50	Same as Run 43, except circumferential clamp applied somewhat too tight, thus moderate resonance was inadvertently obtained.	Moderate	Light
51-53	Same as Run 43.		
56-57	Similar to Runs 39-42. Pipe instrumented to detect ovalling mode.	Strong	No Data

* Resonance effect with respect to Type A thermowell typified by a resonance amplitude peak at about 35 ft/sec flow velocity; with respect to Type B thermowell a steep monotonic rise with increasing flow velocities above about 45 ft/sec.

** In addition to the above a resonance amplitude peak of Type B thermowell observed after Run 38 and during Run 40 at 58 ft/sec.

TABLE 2: FFTF THERMOWELL PLANT TEST SERIES SUMMARY

Date	Test	Purpose	Result
12/2/78	Sec. Loop #3 run to 1080 RPM @ 400°F	Vibration Mode charcterization with regard to outer stem, plus additional thermowells were instrumented to determine the effect of removing top piece (T/C & connector).	The three noisy thermowells definitely responded higher than others in Loop 3. Vibration was highest at thermowell top (simple beam motion) but removing top had little effect on stem.
12/5/78 12/6/78 12/20/78	Sec. Loop #4 to 1080 RPM @ 400°F	Test to measure effect of external collar & effect of an external clamp, plus the effect of adjusting the downstream pipe clamp.	The external collar had no effect on the vibration. Adjusting clamps both upstream and downstream definitely affected the thermowell vibration.
12/27/78	Sec. Loop # 2 Survey to 1110 RPM @ 400°F + audible monitoring.	Determine if thermowells in Loop #2 secondary are vibrating at high amplitudes.	No singing or high amplitude vibration detected.
1/17/79 1/19/79 1/20/79	Primary Loops 1, 2 & 3 Survey to 1110 RPM @ 400°F + audible monitoring.	Determine if thermowells in Primary Loops 1, 2, 3 are vibrating at high amplitudes.	No singing or high amplitude vibration detected.
1/24/79	Sec. Loop #1 Survey to 1110 RPM @ 400°F + audible monitoring.	Determine if thermowells in Secondary Loop # 1 are vibrating at high amplitudes.	No singing or high amplitude vibration detected.
1/27/79	Sec. Loop #3 Test to 1110 RPM.	Determine the effect of dampening insert device & make a tip deflection measurement.	The un-modified dampening device was ineffective. Probe to measure tip deflection was somewhat effective in reducing the vibration amplitude. Tip displacements were imperceptably low.
2/12/79	Primary Loops 1, 2, 3 Pump Speed scans to 1000 RPM @ 600°F audible monitoring.	Determine if higher temperature adversely affected thermowell vibration at 600°F.	No singing or high amplitude vibration detected.

TABLE 2: FFTF THERMOWELL PLANT TEST SERIES SUMMARY (CONTINUED)

Date	Test	Purpose	Result
2/15/79	Sec. Loops 1, 2, 3 pump speed scans to 1000 RPM @ 600°F audible monitoring.	Determine if higher temperature adversely affected thermowell vibration at 600°F.	No singing or high amplitude vibration detected.
2/22/79	Audible monitoring & accelerometers installed on selected thermowells during MIST.	Ensure thermowell vibration would not become a hazard during MIST.	No singing or high amplitude vibration detected.